Can Electric Charges and Currents Survive in an Inhomogeneous Universe?

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(Dated: September 4, 2006)

Although observations point to the neutrality of the present-day universe, many mechanisms are known that could have created an excess of charge at early times, a process we refer to as electrogenesis. We consider the evolution of electric charge asymmetries which arise during the history of the universe. We show that the dynamics of cosmological perturbations drive the universe to become electrically neutral and current-free to a high degree of accuracy on all scales, regardless of initial conditions or early electrogenesis. The forced neutrality relaxes constraints on the generation of electric charge in the early universe, while the erasure of currents disfavors many mechanisms for the early origins of large-scale magnetic fields.

PACS numbers: 11.15.Ex, 95.30.Cq, 95.30.Qd, 98.62.Ai, 98.80.Cq

arXiv:astro-ph/0609031 v1 1 Sep 2006

Conservation laws and conserved quantities are among the most powerful tools in particle physics and cosmology. Empirically conserved quantities are often related to symmetries, whether they be discrete space-time symmetries (such as CPT), global symmetries (such as baryon and lepton numbers), or gauge symmetries (such as color and electric charges). Although no direct experimental evidence exists for the violation of these conservation laws [1], the matter-antimatter asymmetry is a compelling indicator that perhaps baryon number conservation was violated at some point in the past [2]. Indeed, so long as the Sakharov conditions [3] are met, baryon number violation appears to be quite likely. Many mechanisms exist that could explain the generation of a baryon asymmetry (baryogenesis), including the decay of GUT-scale particles [4], sphaleron processes [5] at the electroweak scale [6], sphaleron processing of a lepton asymmetry [7], or through a coherent scalar field [8].

In a similar fashion to the global symmetry preserving baryon number, it may be possible to break the gauge symmetry preserving electric charge conservation. These scenarios can result in a process we refer to as *electrogenesis*, since they admit the production of a net electric charge in the universe. Perhaps the simplest pathway for electrogenesis is a theory where the electromagnetic gauge symmetry $\mathrm{U}(1)_{\mathrm{em}}$ was temporarily broken in the past, only to be restored later at lower temperatures. Langacker and Pi [9] demonstrated this possibility in the context of grand unification, while Orito and Yoshimura [10] and Nambu [11] showed that electrogenesis is possible in higher dimensional theories such as Kaluza-Klein. Another possibility that could lead to electrogenesis is that the $\mathrm{U}(1)_{\mathrm{em}}$ symmetry is not exact. This arises in variable speed-of-light cosmologies [12], varying-α theories [13], extensions of the standard model with massive photons [14], brane-world models [15], and models admitting electron-positron oscillations [16].

The idea that the universe could possess an excess of electric charge was first proposed by Lyttleton and Bondi [17], with possibly important cosmological consequences. Their treatment, as well as others [10, 18, 19], assumes that once a net electric charge is created and the charge conservation symmetry is (at least approximately) restored, the amount of electric charge within a comoving volume remains constant. There are observational constraints on the charge-per-baryon (Δ) of the universe at different epochs: the anisotropies of cosmic rays place a constraint that at present, $|\Delta| < 10^{-29}\,e$ [10]; the isotropy of the microwave background constrains $|\Delta| < 10^{-29}\,e$ at $z \simeq 1089$ [20]; and big bang nucleosynthesis requires that $|\Delta| \lesssim 10^{-32}\,e$ at $z \simeq 4 \times 10^8$ [21]. However, charge conservation still allows the local charge to change, provided there is a flow of current. We have recently shown that gravitational forces, in combination with Coulomb forces and Thomson scattering, all impact the evolution of a charge asymmetry [22]. In this letter we examine the evolution of a net electric charge after electrogenesis, and study the associated cosmological ramifications. Although the framework deals strictly with inhomogeneities at a specific wavenumber k, the results are valid in the limit $k \to 0$, and thus we remark on a global excess of charge.

A realistic cosmological model of the universe will necessarily include inhomogeneities on both subhorizon and superhorizon scales, as mandated by inflation. An excellent treatment of the linear evolution of these perturbations, including the photon, neutrino, baryonic, and dark matter components, is given in Ma and Bertschinger [23]. As an electric charge asymmetry is expected to possess the same type of initial inhomogeneities as a baryon asymmetry [18], the evolution of electric charge over- and under-densities should be calculable in the same fashion. While it is possible that a cosmological charge asymmetry could manifest itself in exotic forms, these possibilities are unsupported by experiment. This includes searches for fractionally charged particles [19, 24], or a difference between the strength of the proton and electron charges [25]. We therefore consider that if a cosmic charge asymmetry exists, it is due to a difference between the numbers of protons and electrons.

We choose to work in the conformal Newtonian gauge, defined by the metric

$$ds^2 = a^2(\tau)[-(1+2\psi)d\tau^2 + (1-2\phi)dx^i dx_i], \qquad (1)$$

where ϕ and ψ describe the scalar-mode inhomogeneities. Including Coulomb interactions and Thomson/Compton scattering with photons the evolution equations for protons and electrons become [22]

$$\begin{aligned} \dot{\delta}_i &= -\theta_i + 3\dot{\phi}, \\ \dot{\theta}_i &= -\frac{\dot{a}}{a}\theta_i + c_s^2 k^2 \delta_i + k^2\psi \\ &\quad + \Gamma_i(\theta_\gamma - \theta_i) + \frac{4\pi q_i e a^2}{m_e}(n_p - n_e), \end{aligned} \qquad (2)$$

where i is p for protons and e for electrons, n_p and n_e are the local number density of protons and electrons, q_p and q_e are the proton $(+e)$ and electron $(-e)$ charges, and Γ_i is the (conformal time) rate of momentum transfer due to photon scattering with charged particles,

$$\Gamma_e \equiv \frac{4\bar{\rho}_\gamma n_e \sigma_T a}{3\bar{\rho}_e}, \qquad \Gamma_p = \left(\frac{m_e}{m_p}\right)^3 \Gamma_e. \qquad (3)$$

The Thomson cross section (σ_T) for electrons is replaced with the Klein-Nishina form for temperatures $T \gtrsim m_e$ [26]. By taking the difference between the density and velocity fields for electrons and protons, a set of evolution equations governing the evolution of a net charge within a given volume is obtained. The equations for δ_q and θ_q, where $\delta_q \equiv \delta_p - \delta_e$, $\theta_q \equiv \theta_p - \theta_e$, are

$$\begin{aligned} \dot{\delta}_q &= -\theta_q \\ \dot{\theta}_q &= -\frac{\dot{a}}{a}\theta_q + c_s^2 k^2 \delta_q - \Gamma_e\left(\theta_\gamma - \theta_b + \theta_q\right) + \omega^2\,\delta_q, \end{aligned} \qquad (4)$$

to linear order, where $\delta_b = (m_p\delta_p + m_e\delta_e)/(m_p + m_e)$ is the baryonic mass density perturbation and $\omega^2 = 4\pi n_e e^2 a^2/m_e$ is the (conformal time) plasma frequency.

In our previous paper [22], we investigated the effects of the source term in equation (4), proportional to $\theta_\gamma - \theta_b$, in the absence of any initial asymmetry. We found that a small asymmetry, of order $\delta_q \sim 10^{-34}$ on Mpc scales, is generated near the time of recombination. In this paper, we study the fate of an initial asymmetry. We note that since equations (4) are linear, these two cases evolve independently of one another. As the rates Γ_e and ω are typically much greater than the expansion rate $\dot{a}/a$ before decoupling, and much greater than the term $c_s^2 k^2$ on all but the smallest scales, the latter terms can be neglected, and equations (4) can be simplified into the single equation

$$\ddot{\delta}_q + \Gamma_e\dot{\delta}_q + \omega^2\delta_q = 0. \qquad (5)$$

An initial asymmetry evolves as a damped harmonic oscillator, with slowly varying coefficients. If the coefficients were constant, we would have the usual solution, with two modes,

$$\delta_q = c_1 e^{s_1\tau} + c_2 e^{s_2\tau}, \qquad (6)$$

where c_1 and c_2 are undetermined constants, and $s_{1,2}$ are the two roots of $s^2 - \Gamma_e s + \omega^2 = 0$,

$$s_{1,2} = -\Gamma_e/2 \pm \sqrt{\Gamma_e^2/4 - \omega^2}. \qquad (7)$$

For $\Gamma_e/2 > \omega$, the modes are a fast and a slow decay, while for $\Gamma_e/2 < \omega$, there is an oscillation with a damped envelope.

The rates Γ_e and ω in fact vary with expansion, as $\Gamma_e \propto a^{-3}$ and $\omega \propto a^{1/2}$, and so change slowly on the expansion timescale. As a result, the arguments of the exponentials in equation (7) change from $s\,\tau$ to $\int s\,d\tau$, as can be seen straightforwardly by changing variables to the logarithm of the asymmetry, $X = -\ln(\delta_q/\delta_0)$ where δ_0 is the initial asymmetry, and its derivative, the damping rate $s = \theta_q/\delta_q$. From equations (4), these quantities satisfy

$$\dot{X} = s, \qquad \dot{s} = -\frac{\dot{a}}{a}s + c_s^2 k^2 + \omega^2 - \Gamma_e s + s^2, \qquad (8)$$

where the rates ω and Γ_e are again much greater than the expansion rate $H = \dot{a}/a$ and the term $c_s^2 k^2$. We expect $\dot{s}$ is also small, since the rates Γ_e and ω vary slowly. In this approximation, the damping rate s is a root of $s^2 - \Gamma_e s + \omega^2 = 0$, as above, and

$$X = \int s\,d\tau = \int da\,\frac{s}{\dot{a}} = \int \frac{da}{a}\,\frac{s}{H}. \qquad (9)$$

The quantity s/H represents the rate of logarithmic damping per Hubble time, or damping per log expansion factor.

Figure 1 demonstrates dramatically that the damping is so powerful as to wipe out a charge asymmetry for a large window around the epoch of critical damping. The figure shows the logarithm of the damping factor for both a charge asymmetry $\delta_q \propto e^{-X}$ and a current $J \propto \theta \propto s\,e^{-X}$. At early times, an initial charge asymmetry decays according to the slow-decay mode solution of equations (8), while an initial current follows the fast-decay mode. For values of $X \gtrsim 10^2$, an initial charge asymmetry of order 1 is reduced to less than one excess proton or electron within our present horizon.

The results in Figure 1 indicate that any excess charge created at temperatures above 100 GeV will be entirely wiped out at roughly the electroweak scale, and any electrogenesis that concludes between $T_{\rm EW}$ and $T_{\rm CMB}$ will also be driven away in a time much less than the Hubble time. Furthermore, any relic current created at temperatures $T > T_{\rm CMB}$ will be driven away in a similar fashion. We therefore conclude that the dynamics of the universe, via scattering and Coulomb interactions, force the universe to an electrically neutral, current-free state, independent of initial conditions, inflationary remnants, electrogenesis, and phase transitions that may leave charges or currents behind.

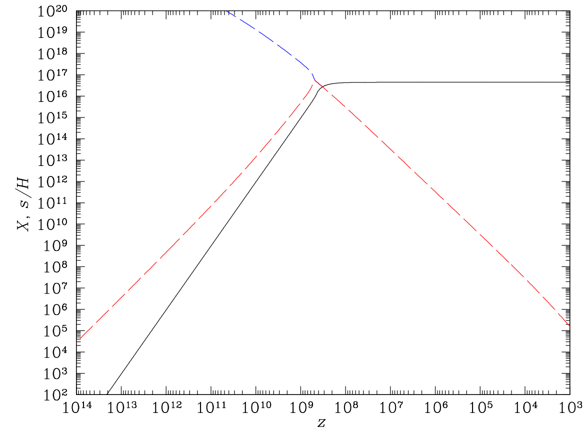

FIG. 1: The logarithm of the damping factor $X = -\ln\delta$ (solid curves) and the normalized damping rate per Hubble time s/H (dashed curves), as a function of redshift. The lower dashed curve represents the slow decay mode, which describes the evolution of an initial charge, while the upper dashed curve illustrates the fast mode, describing the damping of an initial current. After critical damping ($z \approx 10^9$), the two dashed curves evolve together. For damping rates $s/H \gtrsim 10^5$, any initial charge or current will be completely driven away in less than one Hubble time, which happens for excess charges for values of z between 10^3 and 10^{13} and for currents for $z \gtrsim 10^3$.

The damping effect of photon scattering and the Coulomb force on charges and currents created at early times has important implications for cosmology. Since the initial conditions on δ_q are unimportant, the source term in equation (4) provides the only significant late-time asymmetry. After any initial charge is wiped out, δ_q continues to evolve according to the dynamics in equation (4), where the source term determines δ_q. Results from our previous work [22] indicate that the typical charge-per-baryon on the scale of the present horizon is $|\Delta| \sim 10^{-46}\,e$, a result that is valid since the present horizon is still in the linear regime of structure formation. Our results satisfy the observational constraints that $|\Delta| \lesssim 10^{-32}\,e$ at nucleosynthesis and $|\Delta| \lesssim 10^{-29}\,e$ at recombination. However, it is important to realize that these experimental limits do not constrain the possibility of either electrogenesis or charge conservation violation at early times. Indeed, any measurements of $|\Delta|$ which probe the temperature range $T_{\rm EW} \gtrsim T \gtrsim T_{\rm CMB}$ cannot constrain charge generation, as $|\Delta|$ is driven to 0 via the dynamics of charged particles in an expanding universe.

Since any relic charge excess created via electrogenesis is driven away, it becomes of interest to ask whether the possibility exists for detecting whether or not there was significant electrogenesis in the universe's past. To this end, it is necessary to examine the phenomenological consequences of electrogenesis. Just as GUT-scale baryogenesis has phenomenological consequences such as proton decay, electrogenesis should also have consequences for particle physics. Each specific model that admits electrogenesis will have its own associated phenomenology. Some consequences of models admitting charge nonconservation have been worked out [27], with various distinct experimental signatures having been (unsuccessfully) searched for [28]. The physical possibilities if either Lorentz invariance or the $\mathrm{U}(1)_{\rm em}$ symmetry are broken is quite rich and varied, and deserve further examination.

Also of cosmological importance are the implications for magnetic fields in the early universe. If large-scale currents are truly driven away, as in Figure 1, then not only are magnetic fields generated by a charge asymmetry [18] ruled out, but all magnetogenesis scenarios which rely on a relic current persisting from early times are disfavored as well. There is extensive literature on magnetic fields generated via early-universe physics, as electric currents can arise from a large release of energy over a short period of time, e.g. from a phase transition. These currents (and hence magnetic fields) could have been generated during the QCD phase transition [29, 30], the electroweak phase transition [30, 31], or via various processes arising in certain models of inflation [32]. There are contentions that small-scale fields could then be transferred to larger scales if necessary [33]. However, since these currents do not have a source driving them after their creation, the expansion dynamics of the universe ought to damp them away very rapidly, according to the fast decay mode of Figure 1. Unless there is some way to prevent the currents and fields from being driven away, these scenarios are no longer viable possibilities for magnetogenesis.

Strictly, these calculations apply to asymmetries at finite Fourier wavenumber k, but the dependence on k is unimportant and vanishes as $k \to 0$. Thus, it appears that even a global charge asymmetry is driven to zero. At first glance, this may seem to violate the principle of charge conservation, but we recall that currents carry away excess charge while still satisfying the continuity equation. An intuitive (but not rigorous) picture is to consider an expanding universe containing homogeneous proton and electron fluids free to expand at different rates. In the Newtonian limit, with spherical symmetry, an excess of positive charge increases the expansion rate for protons and decreases the expansion rate for electrons, and the total charge in a given volume can decrease even though charge is locally conserved. On closer examination, this construct does not work in detail; different expansion rates require a radial flow of protons relative to electrons, and such a universe could be isotropic about only one center. The flow may also require relativistic velocities. However, the mechanism can apply on arbitrarily large finite scales, and to reduce a charge asymmetry of order the mass density inhomogeneity (10^{-5}) over the scale of the horizon requires a relative velocity of $\mathcal{O}$(km/s), or a bulk fluid displacement of $\lesssim 1\,$Mpc.

Although we have accounted for high-energy effects in electron-photon scattering [26], we have not done this for protons. At very high temperatures, non-relativistic photon-proton scattering is not a good approximation, as protons were dissociated into a quark-gluon plasma at temperatures above the $\Lambda_{\rm QCD}$ scale. Furthermore, we have not taken into account possible shielding effects on cosmological scales, which, if present, could cause the effective Coulomb force to fall off faster than $1/r^2$ for sufficiently large distances. A more sophisticated treatment may be needed to extract the exact behavioral details at these high energies. Nontheless, we expect that the damping rate will remain large compared to the Hubble expansion rate; thus our conclusions should remain valid.

The overall conclusion which can be drawn from this work is that any net charge or current in the universe created above a temperature of $T \sim 1\,\mathrm{eV}$ is driven away by cosmological dynamics. This indicates that a net charge or current of any magnitude could be generated at the electroweak scale, at the time of Higgs symmetry breaking, at the time of supersymmetry breaking, at the end of inflation, or at the grand unification scale, and the universe would not be discernibly different from a universe that was electrically neutral and current-free at all times. The possibility that the universe underwent electrogenesis at some point is intriguing and rich with possibility. Although the phenomenological consequences of electrogenesis have been elusive thus far, evidence for its existence would profoundly alter our cosmological picture of the universe.

We thank Charles Thorn for useful discussions concerning gauge symmetries. E.R.S. acknowledges the Institute for Fundamental Theory at University of Florida for support during the completion of this work.

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